Habitability of Earth-mass Planets and Moons in the Kepler-16 System

B. Quarles, Z. E. Musielak and M. Cuntz

Department of Physics, University of Texas at Arlington

Arlington, TX 76019;

billyq@uta.edu; zmusielak@uta.edu; cuntz@uta.edu

ABSTRACT

We demonstrate that habitable Earth-mass planets and moons can exist in the Kepler-16 system, known to host a Saturn-mass planet around a stellar binary, by investigating their orbital stability in the standard and extended habitable zone (HZ). We find that Earth-mass planets in satellite-like (S-type) orbits are possible within the standard HZ in direct vicinity of Kepler-16b, thus constituting habitable exomoons. However, Earth-mass planets cannot exist in planetary-like (P-type) orbits around the two stellar components within the standard HZ. Yet, P-type Earth-mass planets can exist superior to the Saturnian planet in the extended HZ pertaining to considerably enhanced back-warming in the planetary atmosphere if facilitated. We briefly discuss the potential detectability of such habitable Earth-mass moons and planets positioned in satellite and planetary orbits, respectively. The range of inferior and superior P-type orbits in the HZ is between 0.657 to 0.71 AU and 0.95 to 1.02 AU, respectively.

Subject headings: astrobiology — binaries: general — celestial mechanics — planetary systems — stars: individual (Kepler-16)

1. Introduction

Kepler-16 constitutes a remarkable binary system containing a circumbinary extra-solar planet as reported by Doyle et al. (2011) and suggested by Slawson et al. (2011). The exoplanet was observed by the NASA Kepler spacecraft using the planetary transit method, which greatly enhances the confidence in the reality of the planet and provides unusually precise information about its physical parameters. There is a significant previous array of observations of planets in binary and multiple stellar systems (e.g., Patience et al. 2002;

Eggenberger et al. 2004, 2007; Bonavita & Desidera 2007; Mugrauer & Neuhäuser 2009; Raghavan et al. 2010), which also includes a small group of proposed circumbinary planets in contact binaries (with little chance for providing habitable environments) outside the common envelopes of their Roche lobes (Lee et al. 2009; Qian et al. 2010; Beuermann et al. 2010, 2011).

The Kepler-16 system consists of two stars, i.e., the primary with a mass of $M_1 \simeq 0.69\ M_\odot$ and the secondary with $M_2 \simeq 0.20\ M_\odot$, and a giant planet with properties comparable to Saturn. The orbit of the planet is almost circular and encompasses both stars. It takes nearly 229 days for the planet to complete one orbit. The orbits of all three objects are almost precisely confined to one plane (i.e., within 0.5°). Doyle et al. (2011) provided detailed information about the orbital and physical parameters of the system; however, they did not address issues concerning the possible habitability of the system. Obviously, it is the ultimate quest of the Kepler Mission to discover Earth-mass planets and moons located in the habitable zones (HZs) of their host stars. Therefore, it is the main objective of this paper to demonstrate that habitable Earth-mass planets and exomoons in stable orbits are, in principle, possible in the Kepler-16 system. Moreover, such objects can potentially be detected by the currently operating Kepler mission. This paper is structured as follows: In Sect. 2, we outline our theoretical approach by commenting on the stellar HZ as well as the employed numerical methods and considered system configurations. In Sect. 3, we describe our results and discussion. Our conclusions are given in Sect. 4.

2. Theoretical Approach

2.1. Standard and Extended Habitable Zones

The Kepler-16 system contains two closely orbiting stars (a_b = 0.22431 AU) with the primary (Kepler-16A) producing a substantially larger amount of photometric flux than the secondary (Kepler-16B) (i.e., $F_\mathrm{B}/F_\mathrm{A} = 0.01555$). This allows us to calculate the size of the HZ in this system by solely taking into account the radiation of the primary. We compute the boundaries of the HZ in this system by using the fitting formulas of Underwood et al. (2003) based on the previous work by Kasting et al. (1993) (also using a corrected value for the solar effective temperature), which are categorized by decisive atmospheric conditions of the Earth-mass test planet. Appropriate definitions for the inner and outer boundary of the stellar HZ are based on the runaway and maximum greenhouse effect, respectively, for the planetary atmosphere; this standard HZ is found to extend from 0.36 to 0.71 AU for Kepler-16A. This result proves to be also consistent with the more recent work by Selsis et al. (2007) for the case of recent Venus to early Mars-type conditions. In addition, we use the work by Mischna et al. (2000) to calculate the so-called extended HZ, which requires a more extreme

planetary atmosphere with significantly enhanced back-warming; its outer boundary extends out to about 2.0 AU in the Solar System (Mischna et al. 2000) and, correspondingly, to 1.02 AU in Kepler-16. With the giant planet (Kepler-16b) positioned at 0.7048 ± 0.0011 AU, it is found to be located very close to the outer edge of the standard HZ, but well within the extended HZ (see Fig. 1).

2.2. Numerical Methods and System Configurations

The main aim of this paper is to investigate numerically the orbital stability of an Earth-mass object (i.e., exoplanet or exomoon) in both the standard and extended HZ of the Kepler-16 system. Our numerical methods are based on the Wisdom-Holman mapping technique as well as the Gragg-Burlisch-Stoer algorithm (Grazier et al. 1996). We integrate the resulting equations of motion forward in time for 1 million years using a fixed/initial (WH/GBS) time step of 10^{-4}. The relative error in energy is calculated to determine when the integration methods fail and the onset of orbital instability occurs. A second check for stability is performed using the method of Lyapunov exponents (see Wolf et al. 1985) with a special emphasis on the maximum Lyapunov exponent (MLE). Our numerical simulations are designated as stable when they terminate with a relative energy error smaller than 10^{-9} and possess a MLE that is asymptotically approaching zero (Quarles et al. 2011).

By adding an Earth-mass object we consider the Kepler-16 system as a 4-body system; therefore, the Earth-mass object can possibly exist in 6 different orbital configurations. The object can move outside the orbits of the two more massive objects in a planetary (P)-type orbit or around any one of the massive components in a satellite (S)-type orbit. The putative Earth-type object could possibly exist in one of the following classes: 3 S-type orbits, 2 P-type orbits, or 1 Trojan exomoon. The S-type configuration would correspond to orbits around Kepler-16A, Kepler-16B, or Kepler-16b, i.e., the Saturnian planet. Due to the general definition of a moon, any S-type orbit revolving around an exoplanet would inherently constitute an exomoon. The P-type orbits would be classified as being either inferior or superior to the Saturnian planet. The Trojan exomoon orbit could exist at either equilateral equilibrium point, L4 or L5.

The numerical setup of our simulations is based on the system parameters presented by Doyle et al. (2011), see Table 1, as well as adequate initial conditions. We chose an initial configuration with the more massive stellar component (Kepler-16A) near the center of our barycentric coordinate system. The less massive stellar component (Kepler-16B) is initialized to the left of Kepler-16A at the apastron starting position so that the initial separation of the stars is $a_{\rm b}(1+e_{\rm b}) = 0.260$ AU. Kepler-16b is initialized to the right of the primary at the

apastron starting position using the parameters $(a_{\rm p}, e_{\rm p})$ given by Doyle et al. (2011). The Earth-mass object is initialized to the right of the primary at the apastron starting position. All bodies in this system are given initial velocities in the counter-clockwise direction relative to the center of mass using the known eccentricities of the respective bodies. The initial conditions of the test planet are chosen with respect to the initial starting distance a_0 and eccentricity e_0.

In our simulations we refrain from considering S-type orbits around the stellar components as well as P-type orbits with initial semi-major axes less than the inner boundary of the standard and extended HZ. Our aim is to find stable orbits for the test Earth-mass planet within the standard and extended HZ. Therefore, in our computations the parameter a_0 is selected to range from 0.36 to 1.02 AU in increments of 0.001 AU, allowing us to investigate possible P-type planetary orbits as well as S-type orbits for the exomoon; furthermore, the parameter e_0 is selected to range from 0.0 to 0.5 in increments of 0.01. We also investigate the case of Trojan exomoons with parameters (a_0, e_0) equal to the initial parameters of Kepler-16b, where the exomoon is placed in a position that corresponds to a point preceding Kepler-16b by 60°.

In addition to our full simulations for the 4-body system, we also give an estimate of the outer limit of the S-type orbital stability boundary and the inner limit of the P-type orbital stability boundary using the statistical fitting formulas of Holman & Wiegert (1999). These fitting formulas have been deduced using a range of mass ratios, distance ratios, and eccentricities of binaries regarding the elliptical restricted 3-body problem. It is important to note that the eccentricity of the test mass is neglected in this study. However, in our application to the elliptical restricted 4-body problem, these fitting formulas will only allow an estimate for test masses of low eccentricity. Since the perturbations due to the giant planet will be small compared to those of the stellar binary components, we implement these formulas neglecting the presence of this planet. This provides a good approximation of the conditions for stability for the S-type orbits around either of the stars, as well as the P-type orbits in close proximity to the inner boundary of the standard HZ. The obtained estimates are then used to guide our numerical study.

3. Results and Discussion

Although we refrained from considering S-type orbits around the stellar components (see Sect. 2.2), it is possible to estimate the stability limit of S-type orbits near the stellar components using a statistical fitting formula (Holman & Wiegert 1999). Our calculations demonstrate that an Earth-mass planet cannot exist farther than 0.0675 ± 0.0039 AU from

the stellar primary (Kepler-16A) for an S-type orbit due to the perturbations initiated by the stellar secondary (Kepler-16B). This shows that S-type orbits of a habitable Earth-mass planet around either of the stars must be excluded because the stability limit is well within the inner boundary of both the standard and extended HZ (see Sect. 2.1). Concerning the P-type orbits inferior to the orbit of the giant planet, our results demonstrate that such orbits are unstable if the semi-major axis is smaller than 0.657 ± 0.011 AU with respect to the stellar primary. However, inferior P-type orbits are still possible if the test Earth-mass planet has a sufficient eccentricity, allowing the giant planet Kepler-16b to capture it as an exomoon.

Since all bodies in our simulations are initialized at their respective apastron starting position, the test planet is also given the appropriate velocity to allow for capture (see Fig. 2a). This leaves the principal possibility of a habitable Earth-mass planet in a P-type orbit between 0.657 and 0.71 AU, which means that the planet would be located within the standard HZ. However, short-term secular changes for such orbits allow the giant planet to transfer the Earth-mass planet to an orbit outside the standard HZ within 1,000 years (see Fig. 1a), implying that no stable P-type orbits for habitable Earth-mass planets exist inferior to the giant planet. The only stable P-type orbits for Earth-mass planets are those located superior to the giant planet. Our results show that these orbits become stable once their semi-major axes are 0.95 AU or higher, which places them within the extended HZ (see Fig. 1b).

The last class of orbits include those that could result in an habitable exomoon in either an S-type or Trojan configuration. A stable S-type orbit for such an exomoon can be achieved through two separate scenarios. The first scenario is based on the assumption that the possible exomoon formed together with the giant planet, ignoring migration. The second scenario is based on the assumption that the putative exomoon formed initially in a P-type orbit and was captured by the giant planet as a result of migration. This provides additional justification for considering the eccentricity e_0 as a free parameter because the initial state of the capture remains unknown.

The first scenario which involves the exomoon forming from a secondary circumplanetary disk can be estimated through the concept of Hill stability. Similar to the estimations made by Holman & Wiegert (1999) for the elliptical 3-body problem, there have been simulations to determine an approximate stability limit for exomoons orbiting extrasolar giant planets (Domingos et al. 2006; Kaltenegger 2010). These previous general estimations can be used to guide the investigation of this case. Simulations of this scenario were performed by incrementing the parameter e_0 exactly as before, but the parameter a_0 has been incremented relative to the starting position of the Saturnian planet starting from 0.0001 to 0.0240 AU

in increments of 0.0001 AU. The stability boundaries are expected to occur near the Roche limit (inner) and the estimated Hill limit for prograde motion (outer).

The inner boundary is calculated using the given density (see Table 1) of the Saturnian planet and that of Earth, i.e., 5.515 g cm^{-3}. The Earth mean density has been chosen because it best represents what would be considered as Earth-like. Alternatively, the density could be varied as a function of a_0, but our usage of the density is limited to the calculation of the Roche limit about the Saturnian planet. Planetary formation calculations for this system should be considered in future studies to constrain the mass and densities of possible moons orbiting Kepler-16b, which are however outside the scope of this paper. We also calculated the outer boundary assuming a circular orbit (i.e., $e_0 = 0.0$) because it gives the maximum stability as more eccentric orbits have been shown to decrease the stability region (e.g., Domingos et al. 2006). Thus the inner and outer boundaries are estimated as 0.0004 and 0.0168 AU, respectively.

Through our numerical simulation we have determined the stability boundaries to be commensurate with the previous estimates. The stability analyses of these orbits have undergone similar scrutiny in the relative error in energy and maximum Lyapunov exponent. Although we investigated the possibility of eccentric orbits in this scenario, our results show that the stability decreases dramatically as eccentricity is increased so that most of the stable orbits discovered were nearly circular (see Fig. 3a). We point out that this result is also in accordance with the known parameters of the most massive satellites of Jupiter and Saturn.

The second scenario which involves the exomoon attained through capture may be much less probable. However, we determined that there are P-type orbits, where the proper eccentricity can lead to capture into S-type orbits (see Fig. 2a). The results presented in this figure were obtained with $a_0 = 0.619$ AU and the initial starting distance $x_0 = 0.699$ AU, which is superior to the estimated stability limit of 0.657 AU. This places the test planet within the Hill sphere, corresponding to a Hill radius of 0.034 AU from the giant planet, which shows that the influence of the giant planet ranges radially from 0.67 to 0.73 AU with respect to the center of mass. A general trend is that the circular P-type orbits inferior to the giant planet are generally too fast for capture; hence, we considered eccentric orbits. Moreover, the P-type orbits superior to the giant planet are generally too slow for capture resulting in either collision with the giant planet or ejection from the system.

If migration occurred in this system during its formation, this would be the preferred scenario; it would entail a number of ways for a putative exomoon to avoid a chaotic orbit (Kipping 2011). The constraints on natural satellite formation in the Solar System were previously investigated by (Canup & Ward 2006), who also determined the available mass in the circumplanetary disk. However, the latter may not be applicable to the more exotic case

of the Kepler-16 system since the Saturn-like planet exists in close proximity to the so-called snow line. This makes both scenarios to appear equally likely since the migration distance may have been small. Further planetary formation investigations need to be performed to determine a more unique solution.

Finally, we considered the possibility of a Trojan exomoon. The stability of this possible exomoon is ensured by the fact that the mass ratio ($\mu = m_2/(m_1 + m_2)$ with $m_1 = M_1 + M_2$ and $m_2 = M_{\rm p}$) can be calculated and be used as a stability condition for the approximate 3-body problem. This approximation proves to be valid because the proposed Trojan exomoon would always reside at a semi-major axis commensurate with Kepler-16b at the appropriate distance leading or trailing Kepler-16b (see Sect. 2.2). Considering the case where the binary system can act like a point source at the center of mass, we then find the mass ratio, $\mu = 0.000357$, which is much less than the critical value for Trojans, $\mu_0 = 0.03852\ldots$ (Szebehely 1967). Our results obtained for this configuration show that stable Trojans can exist even if the perturbations by Kepler-16B are not completely negligible (see Fig. 2b). The influence of Kepler-16B can transfer the proposed Trojan exomoon from its equilibrium point but it is insufficient to create an instability; instead, the Trojan exomoon would precess along the orbit of Kepler-16b.

4. Conclusions

By performing numerical simulations we explored the possibility of a habitable Earth-mass object in the Kepler-16 system. Although it is beyond the scope of this paper to determine whether such an object exists, we are able to provide information through our orbital stability analyses where to search for it in the realm of further observations. We considered the standard and extended HZ of the system and investigated 6 different orbital configurations. The obtained results show that S-type planetary orbits about either of the stellar components as well as P-type planetary orbits inferior to Kepler-16b's orbit exhibit short-term orbital instabilities. These instabilities would inhibit any form of habitability due to the ejection, collision, or the occurrence of highly eccentric orbits for any possible object (if it had formed). Our main result about habitable Earth-mass planets in this system is that the only stable P-type orbits for such planets are those located superior to Kepler-16b's orbit. Specifically, these orbits become stable once the semi-major axis is 0.95 AU or higher, which places them within the extended HZ. The range of habitable inferior and superior P-type orbits in the HZ is between 0.657 to 0.71 AU and 0.95 to 1.02 AU, respectively.

Our numerical simulations of S-type orbits for an Earth-mass moon captured by the giant planet or formed through a circumplanetary disk show that such orbits are stable and

moreover located in the standard HZ. A highly relevant aspect of the existence of an exomoon orbiting Kepler-16b is that it may help explain the variation between the observed eccentricity and its previously reported value from numerical study (Doyle et al. 2011). Similar to the effects of Earth's Moon, the exomoon could exert possible tidal forces, through a stabilizing torque and angular momentum exchanges, freezing the eccentricity of Kepler-16b at the observationally determined value of 0.0069. As the observations may just be a snapshot in time, other hypotheses concerning the Kozai Mechanism, driving of eccentricity through planet-planet interactions, or possible exomoons, can be considered equally likely and cannot be uniquely identified until further investigations of the system have been performed (Laskar et al. 1993; Barnes & Greenberg 2008). Since the exomoon would lie on the outer edge of the HZ, tidal heating could also play a role in increasing the prospects of habitability (Barnes et al. 2009; Dressing et al. 2010). We also considered the possibility of a Trojan exomoon present at one of the equilateral Lagrange points. This is an intriguing case as the exomoon would precess and display a variety of different orbits about L4 or L5, which are all located within the standard HZ. Hence, the existence of habitable exomoons around Kepler-16b is an exciting scenario for facilitating habitability in the Kepler-16 system.

Finally, we want to point out that an Earth-mass planet or moon can potentially be detected by the current Kepler mission. Our suggestion is based on the work by Kipping et al. (2009) who provided evidence that Kepler's instruments should indeed be capable of detecting such objects, specifically, the possible exomoon. In general, Kepler should be able to detect exomoons as small as 0.2 $M_\oplus$ if observers look for the transit timing effects discussed by Kipping et al. (2009). In addition, the realm of circumbinary planets similar to Kepler-16b may prove to be an adequate region for discovering exomoons as it would be possible to obtain the necessary statistical constraints of detection. The 220-day period the Saturnian planet makes it possible to observe 6 transits within 3.6 years of observation, which is well within the extended mission life time of the Kepler spacecraft. It is also noteworthy that the distance to the Kepler-16 is only about 61 parsec, which places the system well within the distance range (0.68 – 386 pc) for detecting Earth-mass planets and exomoons around K and M-type stars.

This work has been supported by the U.S. Department of Education under GAANN Grant No. P200A090284 (B. Q.), the Alexander von Humboldt Foundation (Z. E. M.), and the SETI institute (M. C.). Moreover, it has been supported in part by NASA through the American Astronomical Society's Small Research Grant Program (M. C.). We also would like to thank R. Heller (the referee) for valuable comments.

REFERENCES

Barnes, R., & Greenberg, R. 2008, in IAU Symp. 249, Exoplanets: Detection, Formation and Dynamics, ed. Y.-S. Sun, S. Ferraz-Mello, & J.-L. Zhou (Cambridge: Cambridge University Press), 469

Barnes, R., Jackson, B., Greenberg, R., & Raymond, S. N. 2009, ApJ, 700, L30

Beuermann, K., et al. 2010, A&A, 521, L60

Beuermann, K., et al. 2011, A&A, 526, A53

Bonavita, M., & Desidera, S. 2007, A&A, 468, 721

Canup, R. M., & Ward, W. R. 2006, Nature, 441, 834

Domingos, R. C., Winter, O. C., & Yokoyama, T. 2006, MNRAS, 373, 1227

Doyle, L. R., et al. 2011, Science, 333, 1602

Dressing, C. D., Spiegel, D. S., Scharf, C. A., Menou, K., & Raymond, S. N. 2010, ApJ, 721, 1295

Eggenberger, A., Udry, S., & Mayor, M. 2004, A&A, 417, 353

Eggenberger, A., Udry, S., Chauvin, G., Beuzit, J.-L., Lagrange, A.-M., Ségransan, D., & Mayor, M. 2007, A&A, 474, 273

Grazier, K. R., Newman, W. I., Varadi, F., Goldstein, D. J., & Kaula, W. M. 1996, DDA Meeting No. 27, BAAS, 28, 1181

Holman, M. J., & Wiegert, P. A. 1999, AJ, 117, 621

Kaltenegger, L. 2010, ApJ, 712, L125

Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108

Kipping, D. M. 2011, Ph.D. thesis, University College London (arXiv:1105.3189)

Kipping, D. M., Fossey, S. J., & Campanella, G. 2009, MNRAS, 400, 398

Laskar, J., Joutel, F., & Robutel, P. 1993, Nature, 361, 615

Lee, J. W., Kim, S.-L., Kim, C.-H., Koch, R. H., Lee, C.-U., Kim, H.-I., & Park, J.-H. 2009, AJ, 137, 3181

Mischna, M. A., Kasting, J. F., Pavlov, A., & Freedman, R. 2000, Icarus, 145, 546

Mugrauer, M., & Neuhäuser, R. 2009, A&A, 494, 373

Patience, J., et al. 2002, ApJ, 581, 654

Raghavan, D., et al. 2010, ApJS, 190, 1

Selsis, F., Kasting, J. F., Levrard, B., Paillet, J., Ribas, I., & Delfosse, X. 2007, A&A, 476, 1373

Slawson, R. W., et al. 2011, AJ, 142, 160

Szebehely, V. 1967, Theory of Orbits (New York and London: Academic Press)

Qian, S.-B., Liao, W.-P., Zhu, L.-Y., & Dai, Z.-B. 2010, ApJ, 2010, L708

Quarles, B., Eberle, J., Musielak, Z. E., & Cuntz, M. 2011, A&A, 533, A2

Underwood, D. R., Jones, B. W., & Sleep, P. N. 2003, Int. J. Astrobiol., 2, 289

Wolf, A., Swift, J. B., Swinney, H. L., & Vastano, J. A. 1985, Physica D, 16, 285

This preprint was prepared with the AAS LaTeX macros v5.0.

Table 1: Stellar and Planetary Parameters of Kepler-16

Parameter	Value[a]
Distance (pc)	~ 61
$F_{\rm B}/F_{\rm A}$	0.01555 ± 0.0001
M_1 ($M_\odot$)	0.6897 ± 0.0035
M_2 ($M_\odot$)	0.20255 ± 0.00066
$T_{\rm eff,1}$ (K)	4450 ± 150
R_1 ($R_\odot$)	0.6489 ± 0.003
$P_{\rm b}$ (d)	41.079220 ± 0.000078
$a_{\rm b}$ (AU)	0.22431 ± 0.00035
$e_{\rm b}$	0.15944 ± 0.00061
$M_{\rm p}$ ($M_{\rm J}$)	0.333 ± 0.016
$a_{\rm p}$ (AU)	0.7048 ± 0.0011
$e_{\rm p}$	0.0069 ± 0.001
$\rho_{\rm p}$ (g cm^{-3})	0.964 ± 0.047

Note. — [a]Data as provided by Doyle et al. (2011). All parameters have their usual meaning.

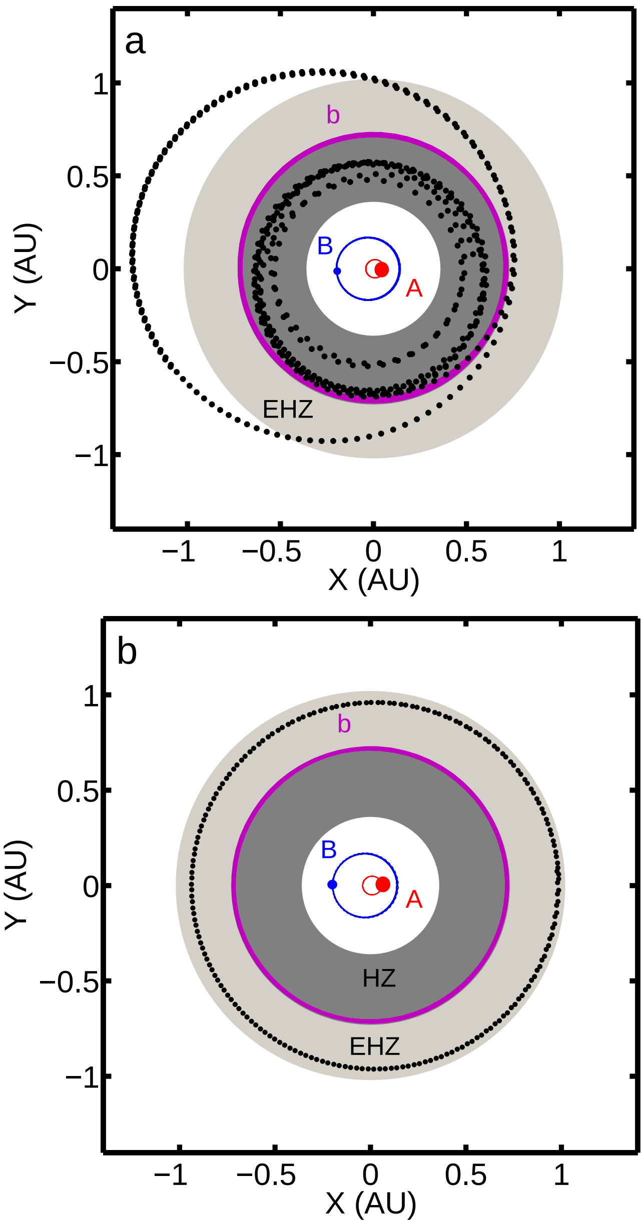

Fig. 1.— (a) Depiction of an unstable P-type Earth-mass planet (*black*) with an initial semi-major axis of $a_0 = 0.504$ AU and an initial eccentricity of $e_0 = 0.06$ to give a starting position at apastron of $x_0 = 0.534$ AU; the stars are given as A (*red*) and B (*blue*). (b) Depiction of a stable P-type Earth-mass planet (*black*) with an initial semi-major axis of $a_0 = 0.951$ AU and an initial eccentricity of $e_0 = 0.03$ to give a starting position at apastron of $x_0 = 0.980$ AU. The dark gray region represents the standard habitable zone (HZ) and the light gray region represents the extended habitable zone (EHZ). The agreement between the orbit of the giant planet Kepler-16b (*purple*) and the outer edge of the standard HZ is coincidental.

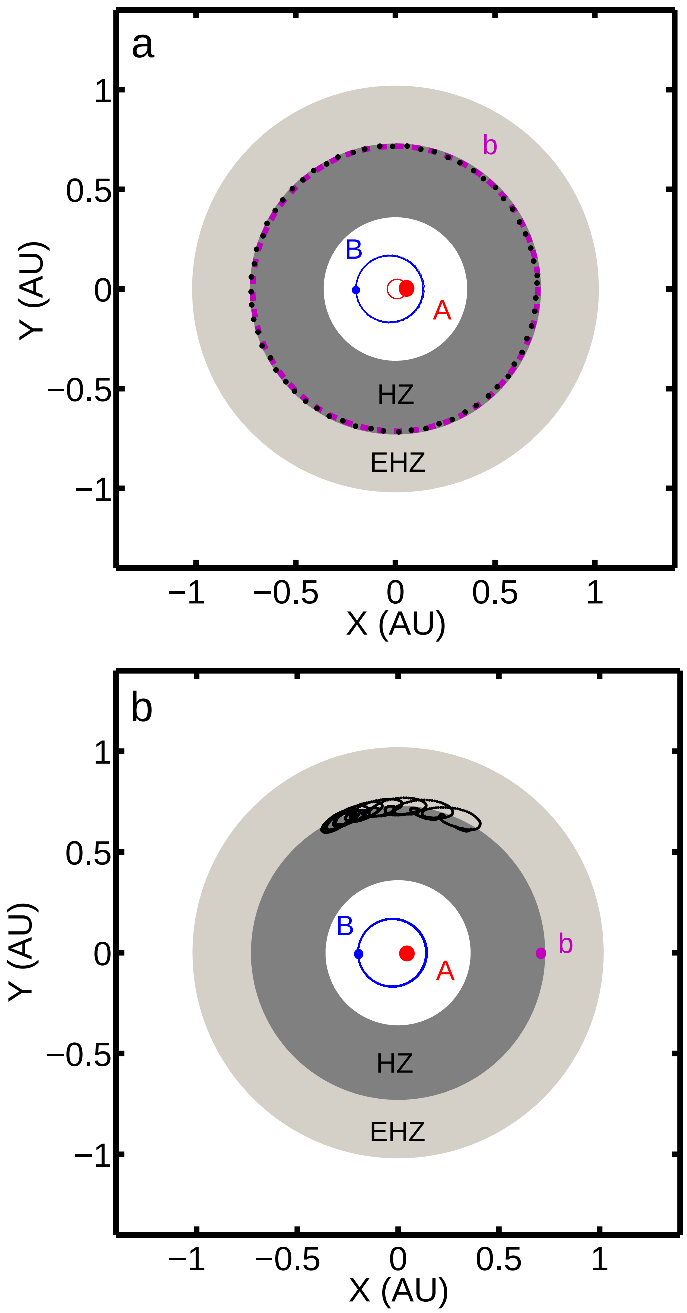

Fig. 2.— (a) Depiction of an S-type *captured* Earth-mass exomoon (*black*) with an initial semi-major axis of $a_0 = 0.619$ AU and an initial eccentricity of $e_0 = 0.13$ to give a starting position at apastron of $x_0 = 0.699$ AU; the stars are given as A (*red*) and B (*blue*). (b) Depiction of a possible Trojan exomoon in a rotating reference frame (*black*) with an initial semi-major axis of $a_0 = 0.7048$ AU and an initial eccentricity of $e_0 = 0.0069$ to give a starting position at apastron of $x_0 = 0.710$ AU. The dark gray region represents the standard habitable zone (HZ) and the light gray region represents the extended habitable zone (EHZ). The agreement between the orbit of the giant planet Kepler-16b (*purple*) and the outer edge of the standard HZ is coincidental.

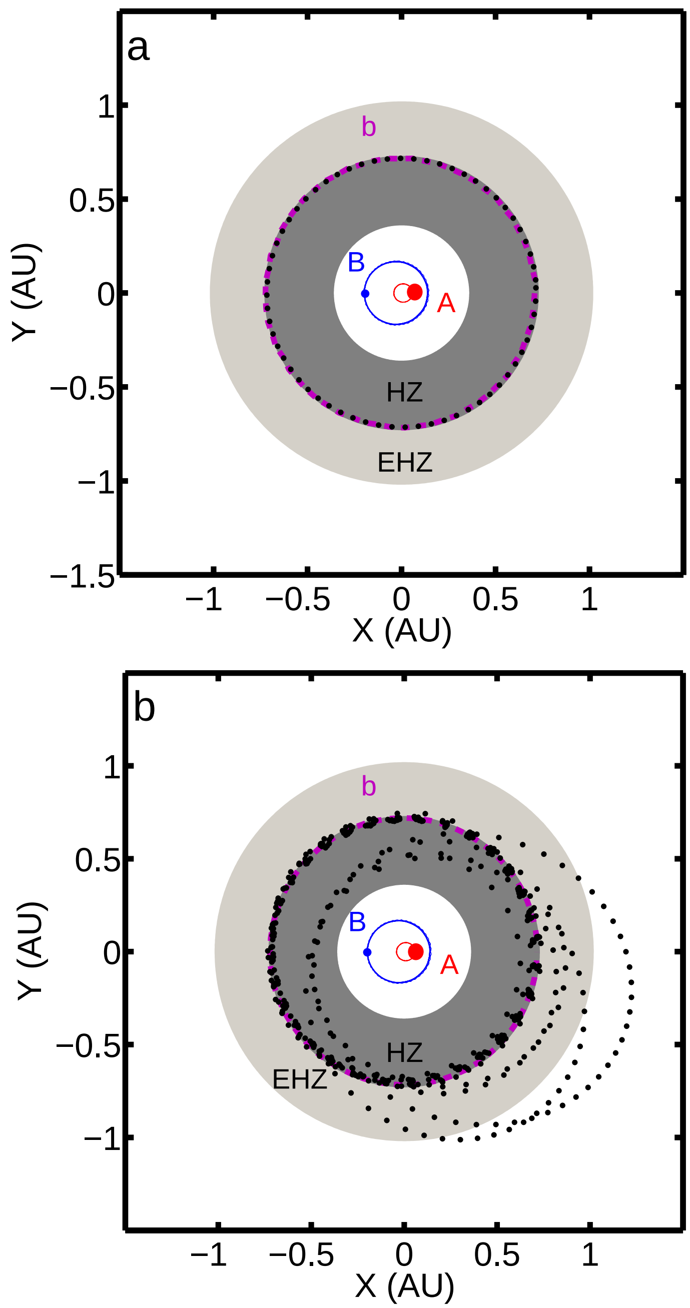

Fig. 3.— (a) Depiction of a stable S-type *coformed* Earth-mass exomoon (*black*) with an initial semi-major axis of $a_0 = 0.715$ AU and an initial eccentricity of $e_0 = 0.0$; the stars are given as A (*red*) and B (*blue*). (b) Depiction of an unstable S-type *coformed* Earth-mass exomoon (*black*) with an initial semi-major axis of $a_0 = 0.721$ AU and an initial eccentricity of $e_0 = 0.0$. The dark gray region represents the standard habitable zone (HZ) and the light gray region represents the extended habitable zone (EHZ). The agreement between the orbit of the giant planet Kepler-16b (*purple*) and the outer edge of the standard HZ is coincidental.